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OIL ANALYSIS PROGRAM GEAR BENCH TESTING.(U)
AUG 76 P J MANGIONE

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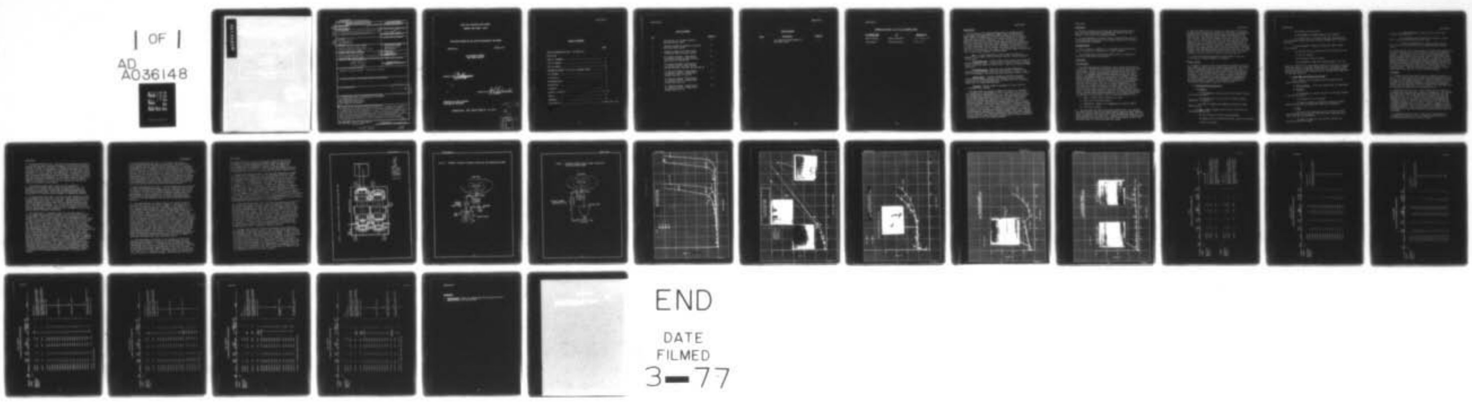

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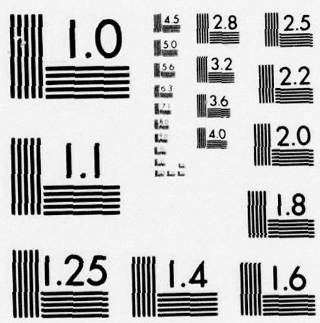

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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Gear Normal Wear/Fatigue Tests
Ryder Research Gear Machine

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of the Navy Oil Analysis Program is to determine the feasibility of identifying wear and failure modes in oil wetted systems by oil analysis evaluation and detection techniques. As part of this effort the NAPTC conducted gear bench tests which simulated wear, scuffing/scoring, and fatigue failure modes in typical mechanical gearing systems. This report presents oil sampling identification/spectrometric oil analysis results and related test data including failure criteria which will be necessary in the total program.

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NAVAL AIR PROPULSION TEST CENTER

TRENTON, NEW JERSEY 08628

PROPULSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

NAPTC-PE-90 AUGUST 1976

OIL ANALYSIS PROGRAM
GEAR BENCH TESTING

Prepared by: P.J. MANGIONE

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APPROVED FOR PUBLIC RELEASE:
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AUTHORIZATION: NAEC PROJECT ORDER NO. PO-5-8020

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CONVERSION FACTORS: SI TO U.S. CUSTOMARY UNITS

TO CONVERT FROM	TO	MULTIPLY BY
Degree Celsius	Degree Fahrenheit	$t_f = 1.8\ t_c + 32$
Newton/metre	Pound-force/inch	5.71×10^{-3}

INTRODUCTION

The Tri-Service Oil Analysis Program under the auspices of the Ground Support Equipment Department (GSED), Naval Air Engineering Center (NAEC) is attempting to determine the feasibility of identifying wear and/or failure modes in oil wetted systems by oil analysis evaluation and detection techniques. As part of this effort, the Naval Air Propulsion Test Center (NAPTC) was authorized by reference 1 to conduct gear bench tests which would simulate wear and failure modes in typical mechanical gearing systems. Basically, by definition, a gear has failed when it can no longer efficiently function in the job for which it was designed. The cause of failure may range from excessive wear to catastrophic breakage as defined below.

Wear: A surface phenomenon in which layers of metal are removed, or "worn away", fairly uniformly from the contacting surfaces of gear teeth.

Pitting/Spalling: Surface fatigue failure which occurs when the material endurance limit is exceeded and is directly related to surface contact stress and number of stress cycles. Spalls are irregular shaped large pits.

Scuffing/Scoring: Rapid wear (by alternate welding and tearing) of tooth surfaces resulting from a failure of the oil film due to overheating of the mesh, thus permitting metal-to-metal contact.

Plastic Flow: A surface deformation from the yielding of surface and sub-surface material (cold working) which is usually associated with softer gear materials, but which can occur in heavily loaded case or through hardened gears.

Fracture: Failure caused by breakage of a whole tooth due to excessive tooth loading.

The gear bench test program at NAPTC was conducted to determine the feasibility of identifying, by used oil analysis, three of the five failure modes discussed above, i.e., wear, pitting and scuffing/scoring when such failures are obtained in the Ryder Gear Machine. These failure modes were selected, to the exclusion of the others, because of metal particle generation which normally occurs in a progressive manner. Basically, the program provided used oil samples from selected tests which would then be analyzed to determine if metal content, particle size, shape or distribution could be associated with the wear or failure modes. In addition to spectrographic oil analysis, ferrographic and X-ray emission analytical techniques will be used for further particle analyses in the overall program. This report presents only the pertinent oil sampling information, spectrometric oil analysis results, and all related test data including failure criteria which will be necessary in the total program analyses.

CONCLUSIONS

1. The tests conducted on the Ryder Gear Machine provided typical gear failures and associated oil samples for extensive particle analyses in the overall oil analysis program.

2. The spectrographic oil analysis results indicated that only the scuffing/scoring failure mode can be readily detected by this quantitative analytical technique.

RECOMMENDATIONS

1. The oil samples be subjected to ferrographic and X-ray emission analytical analyses as defined in the overall program.

2. The Scanning Electron Microscope (SEM) studies be completed on the "end of test" gear tooth surfaces.

DESCRIPTION

Test Equipment

1. The Ryder Gear Machine is basically used to assess the ability of a lubricant to prevent the destruction of gears by the scuffing/scoring failure mode. As such, it is one bench test presently used in the qualification testing of gas turbine lubricants for military specifications. An improved high speed/high temperature model, the Ryder Research Gear Machine (figure 1), was used in this program. The gear machine operates on the four-square principle in that two parallel shafts are connected by two sets of gears; one set is the replaceable test spur gears and the other is a set of helical gears which are integral with the shafts. The load is applied hydraulically to the test gears by the axial movement of one shaft relative to the other. Gear tooth load, then, is a function of helix angle, shaft cross-sectional area (system constants), hydraulic pressure and gear tooth width. The gear machine has also been used in surface fatigue (pitting) studies because system operating parameters can be readily controlled and imposed on the test gears. Some of these main parameters are:

a. Speed - Sliding velocities/Slide roll ratio

b. Load - Tooth load/Hertz stress

c. Temperature - Range of oil temperatures to 426.7°C (800°F)

d. Test oil flow rates

2. The test gears are AISI 9310 aircraft quality steel, case hardened spur gears with 28 teeth at 22.5 degree pressure angle and eight diametral pitch. The mating (load) gears are the same configuration except for tooth width, and operate at 1:1 gear ratio. The gears meet both the metallurgical and dimensional specifications as set forth in Test Method D-1947 of the American Society for Testing and Materials (ASTM).

3. The basic Ryder test oil system is a closed-loop, recirculating system as shown schematically in figure 2. The system is completely isolated from the support oil system (figure 1) which avoids the introduction of wear debris from all other sources except for the test oil pump. The 100 mesh (149 μm) filter was left in the system since its size (filtration) would not interfere with metal particles carried by the oil for subsequent analyses. The original test oil system was later replaced by a second oil system which was used in SKF Industries, Inc., bearing bench tests under the same oil analysis program. The change was made late in the gear bench tests (last two fatigue tests) when NAEC suspected metal particle retention or contamination of the first system from one test to the next. A schematic diagram of the second test oil system is shown in figure 3.

4. A qualified Military Specification MIL-L-23699 oil was used in the test oil system throughout the program.

Method of Test

5. In general, the gear bench test program was designed to provide three types of surface failures common to gear systems. The combinations of operating conditions for the program were selected to produce scuffing/scoring and fatigue failure modes with normal wear considered as the extended operation prior to any pitting fatigue failures. A total of 420 hours of machine time was scheduled for the program. The condition of gear tooth surfaces was monitored by closed circuit T.V. system and photographically documented at prescribed sampling intervals. The planned test procedures for the specific failure modes sought are outlined below:

a. Scuffing/Scoring Failure Mode -

(1) Pre-Test:

(a) Photographs of typical unused tooth surface (minimum of two sets of prints).

(b) Circulate test oil until 73.9°C (165°F) operating temperature is attained.

(c) Take oil samples for background reading (two NOAP sample bottles).

(2) Test - Conduct standard scuff tests at 10,000 rpm with following modifications:

(a) Use 40,300 N/m (230 PPI) load increments.

(b) Break-in run at 40,300 N/m (230 PPI) load for ten minutes.

(c) Take oil samples.

(d) Evaluate scuff and record.

(e) Photographs of average (typical) tooth surface.

(f) Increase load in 40,300 N/m (230 PPI) increments and run ten minutes at each load until 5 percent average scuff is obtained and record.

(g) Photographs of highest, average and lowest scuffed tooth surfaces.

(h) Continue test at constant load for one additional hour.

(i) Take oil samples.

(j) Re-evaluate scuff and record.

(k) Photographs of same tooth surfaces taken in (g) above.

Repeat (f) through (k) for approximate values of 10 percent, 20 percent, 30 percent, etc., to 90 percent average scuffed tooth surfaces. Subsequent photographs at 10 percent, 20 percent, etc., are again highest, average, and lowest scuffed surfaces and not necessarily the same teeth as 5 percent condition.

b. Normal Wear and Fatigue Failure Modes -

Note: Normal wear is assumed during test operation until fatigue pitting occurs.

(1) Test Conditions: 10,000 rpm, ambient test oil temperature

(2) Pre-Test:

(a) Photographs of typical (unused) tooth surface (minimum of two sets of prints)

(b) Circulate oil for 10 minutes

(c) Take oil samples for background reading (two NOAP sample bottles each) before and after the oil is circulated.

(3) Test:

(a) Run-in for 10 minutes at each 40,300 N/m (230 PPI) load increment up to 362,500 N/m (2070 PPI) load. Read and record scuff after each load increment.

(b) Take oil samples at 201,400 N/m (1150 PPI) and 362,500 N/m (2070 PPI) loads.

(c) Take photographs of typical tooth surfaces only at 362,500 N/m (2070 PPI).

(d) If average scuff is less than 10 percent, continue test at constant 362,500 N/m (2070 PPI) load.

(e) Take photographs and oil samples every five hours up to thirty hours and every ten hours thereafter until pitting occurs.

6. The oil samples collected throughout the program were appropriately identified and submitted to NAEC for spectrometric and ferrographic analyses. The analyses will be directed at determining significant changes in metal content, particle size, shape or distribution which can be associated with the type failure mode. In addition to photographic documentation of gear tooth surface appearance, the test gear specimens were given to the Franklin Institute Research Laboratories (FIRL) for Scanning Electron Microscope (SEM) examination in an effort to identify and relate gear teeth surface condition with the oil analysis results. FIRL was contracted directly by NAEC to perform these examinations under the total oil analysis program.

DISCUSSION

1. A summary of the entire gear bench test program is presented in Table I. The table identifies the type test performed and all related oil samples, test times, and gear tooth surface evaluations which are necessary for the projected analyses. In addition, the last column attempts to give pertinent information which describes procedures and/or operations applicable to the oil samples. The individual tests performed and relatable results are discussed below.

2. Scuffing/Scoring Test (GA-) - This initial test was conducted in accordance with the procedures outlined in paragraph 5a. The pre-test and early load schedule were appropriately followed and gave the desired results, i.e., 5 percent scuff was attained and continued operation for one hour at constant load produced an insignificant increase in scuff to 7 percent. The next scuff level attained was 15 percent instead of the 10 percent as directed, but the test was continued at constant load for one hour. After 35 minutes at load, a sudden increase in scuff level was indicated by changes in specific operating parameters. Upon visual inspection by closed circuit T.V., the average scuff level had increased to 80 percent and the test was terminated.

3. Scuffing/Scoring Test (GB-) - This test was aborted and all information discarded when it was determined that the wrong oil was inadvertently used in the test oil system.

4. Scuffing/Scoring Test (GC-) - The first test procedure was repeated in this test with some "controlled" changes in test oil flow which were intended to promote (a) the onset of scuffing at low tooth load (reduced oil flow), and (b) the retardation of scuffing at the high tooth loads (increased oil flow). However, the imposed test oil flow changes proved ineffective in controlling the scuff phenomenon. Consequently, scuffing again increased significantly during the attempted one hour at constant load and the test was terminated. At this point, it was determined that standard scuffing test procedures may be a better method to provide samples of scuffing at 5, 10, 20, 30, etc., percent and the next two tests were conducted in this manner.

5. Scuffing/Scoring Test (GD-) - This test was performed in accordance with standard ASTM scuffing test procedures, i.e., test operation for ten minutes at each load increment and evaluation of the average percent scuff. The procedure provided various scuffing values from 1 to 50 percent and oil samples for appropriate analyses.

6. Scuffing/Scoring Test (GE-) - A second test was conducted following the procedures used in the above (GD-) test. Again, scuff values were obtained which varied from 1 to 70 percent. The random nature of the scuffing phenomenon precludes exact and/or repeatable scuffing values even at the same load setting, e.g., in tests GD- and GE- at the same load of 483,350 N/m (2760 PPI), the scuffing values were 23.8 and 12.2 percent, respectively. This variability is not uncommon in the scuffing failure mode for the Ryder Gear Machine.

7. The spectrometric oil analysis results of iron (Fe) content in the oil samples are presented in figures 4 and 5 for the four scuffing/scoring tests. Figure 4 shows that Fe particle generation increases rapidly once the 22.5 percent average scuff level is reached without regard to time in applying critical scuffing load. By definition, the critical scuffing load (or load carrying capacity) is the tooth load in pounds per inch of tooth width when the average tooth scuff is 22.5 percent. The load carrying capacity for the MIL-L-23699 oil used in this program was approximately 507,880 N/m (2900 PPI). Figure 5 is a composite of the four tests showing Fe particle generation as a function of the average percent scuff. The average ("best fit") curve indicates that in these tests, with 149 micron filtration, destructive failure of gear tooth surfaces by the scuffing/scoring failure mode is highly probable when oil samples exhibit Fe content beyond 35 PPM. It is extremely important to emphasize that this indicated limit or threshold is relatable only to these tests, with the specified test oil system, and under the defined operating conditions and/or procedures. By no means can this quantitative limit be directly applied to actual gear systems. The photographic inserts demonstrate the transition from initial severe scuffing (approximately 21 percent) through severe scuffing/scoring (approximately 50 percent) to destructive scoring (approximately 80 percent) of the gear tooth surface.

8. Normal Wear/Fatigue Test (GF-) - This initial test for the normal wear/fatigue failure modes was conducted in accordance with the procedures outlined under Description paragraph 5b. As specified, following "run-in" of the gears, the test was conducted at a constant load of 362,500 N/m (2070 PPI) for 91.5 hours without fatigue (pitting) failure. The test was continued at an increased tooth load of 402,790 N/m (2300 PPI) without fatigue failure and finally aborted at 111.5 hours (approximately 6.7×10^7 cycles). In this test, oil samples and surface conditions obtained prior to fatigue (pitting) failure, were considered to be representative of normal wear. However, the amount of scuffing incurred generated a quantity of metal particles which would mask any normal wear particles and would preclude meaningful analysis.

9. Normal Wear/Fatigue Test (GG-) - A second fatigue test was conducted following the established procedures, but with increased test oil flow (to restrict scuffing) and at higher constant tooth load (443,000 N/m or 2530 PPI). At this load, two teeth exhibited fatigue spalls after approximately 42 hours of operation. Although a third and fourth tooth spalled at approximately 62 and 72 hours, continued operation indicated no further change and the test was aborted at approximately 92 hours.

10. The spectrographic oil analysis results (Fe content in PPM) of both tests (GF- and GG-) are shown in figure 6. The similarity of the curves and in particular the "no change" in iron content at the first fatigue spall (photographic insert) amply demonstrates the insensitivity of this analytical method for predicting fatigue failure in gear systems. Again, it is obvious that the amount of scuffing incurred would preclude meaningful spectrometric oil analysis which could identify the fatigue failures in these tests. It was further noted that the average percent scuff exceeded 22.5 percent, but that spectrometric oil analysis results were less than 20 PPM of Fe which is significantly less than the 35 PPM at 22.5 percent scuff obtained in the gear scuffing tests. The extension of the amount of scuffing to these high values occurred at tooth loads well below the critical scuff load and thus may be due to long term-constant load operation resulting in less metal particle generation than previously obtained in the accelerated scuffing/scoring tests. The severity of the scuffing/scoring under heavy load may significantly influence total metal particle generation. Again, the observed quantitative differences indicate the danger in selecting a threshold limit from these bench tests.

11. With approximately 50 percent of the scheduled 420 test hours completed, the program was reviewed at a joint meeting with NAEC, FIRL and NAPTC personnel. It was agreed that two additional normal wear/fatigue tests would be conducted with efforts directed to reducing scuffing/scoring and improving cleanliness in the test oil system. To meet these requirements, NAPTC installed a second test oil jet and the "clean" test oil system used in SKF Industries, Inc. bearing tests under the overall oil analysis program. The additional test oil jet

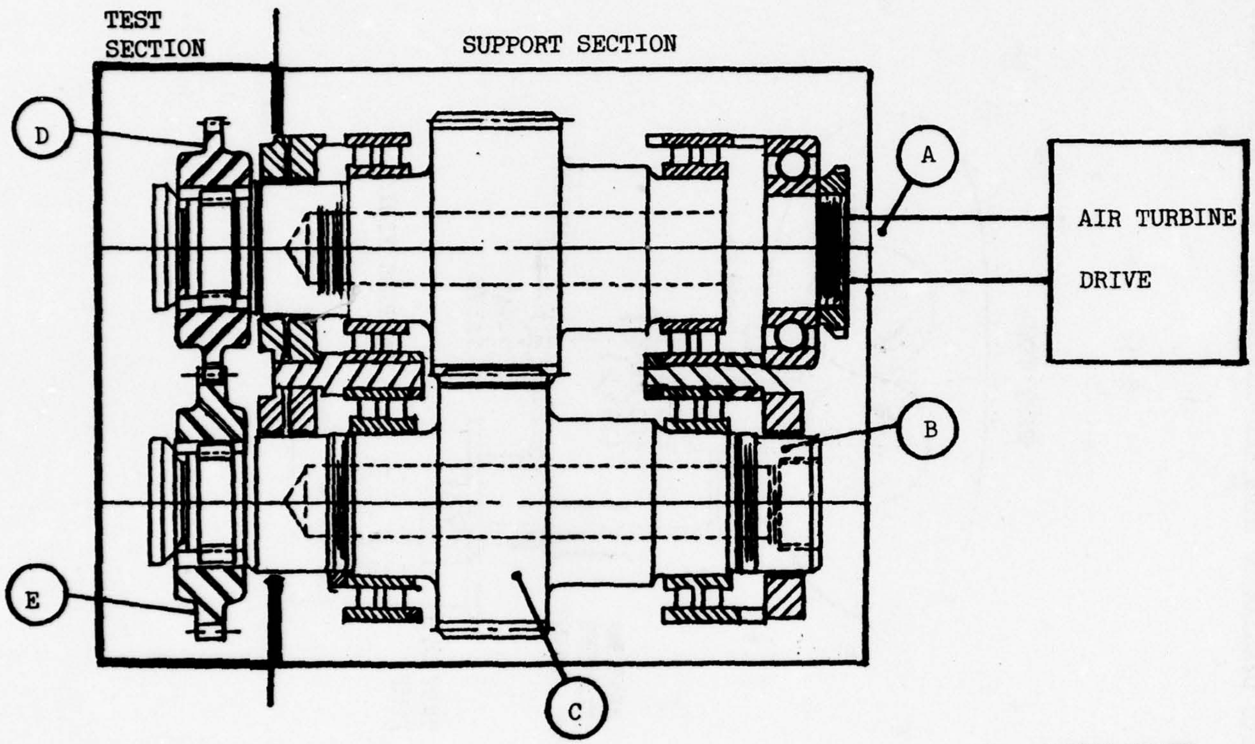
provided more test oil to the gear mesh and a resultant decrease in the amount of scuffing/scoring (subsequently shown in tests GH- and GI- of Table I). The effectiveness of the "clean" oil system can only be determined by ferrographic analysis of initial samples in the final two tests (GH- and GI-). With the Ryder Gear Machine modified as described, the final two tests were conducted and are discussed below.

12. Normal Wear/Fatigue Test (GH-) - This test was essentially a repeat of test GG-, i.e., constant tooth load of 443,000 N/m (2530 PPI) except that test oil flow was significantly increased with the two oil jets. The increased flow resulted in much lower average tooth scuffing through the entire test. At approximately 7 hours, mild pitting was evident on twelve (12) of the twenty-eight (28) teeth. The test was continued at constant load to 91.8 hours with no significant increase in either number or size of pits. An additional 7 hours was completed at increased tooth load without significant change and the test was aborted at 98.8 hours total time. The spectrometric oil analysis results of iron content in the oil samples are presented in figure 7. A tooth showing the typical mild pitting, which developed in the first 7 hours, is shown in the photograph insert. As a result of starting the test with a minimum quantity of oil and losses experienced during the test, oil was added after 51.8 hours of operation as denoted by the discontinuity in the curve (figure 7).

13. Normal Wear/Fatigue Test (GI-) - This test was essentially a repeat of the previous test except that tooth load was increased to 483,350 N/m (2760 PPI) in an attempt to induce larger size pits and/or spalls. Mild pitting was observed on two teeth after 2 hours of operation with a third tooth pitting after 7 hours. The test was continued for 72 hours (total) with no significant change in number or size of pits. The load was then increased to 523,630 N/m (2990 PPI) and after 20 hours (total 92 hours), a fourth tooth developed a medium size spall. Since the average percent scuff was still relatively low, the load was again increased (563,900 N/m or 3220 PPI). However, the pits/or spalls did not change and the test was aborted at 112 hours. Again, the spectrometric oil analysis did not reveal the occurrence of fatigue failures in this test even though average scuff was only 7.3 percent as shown in figure 8.

14. The gear bench tests in the Ryder Gear Machine have successfully produced gear failure modes typically found in gears and/or gear systems. The condition of gear tooth surfaces at various degrees of wear or failure was photographically documented throughout the program. In addition, the gears were forwarded to the Franklin Institute Research Laboratory for SEM evaluation of the gear tooth surfaces at the completion of each test. The tests provided sequential oil samples taken at specific intervals in each failure mode which were then scheduled for extensive analyses in the overall oil analysis program. The spectrometric oil analysis results of iron (Fe) content presented in this report must be incorporated with the ferrographic and X-ray emission results on these same oil samples to meet the objectives defined in the overall program.

FIGURE 1. CROSS-SECTION OF RYDER RESEARCH GEAR MACHINE TEST HEAD



A. DRIVE SHAFT
B. DRIVEN (LOAD) SHAFT
C. HELICAL "SLAVE" GEARS
D. TEST GEAR
E. LOAD GEAR

FIGURE 2. SCHEMATIC DIAGRAM OF STANDARD CLOSED-LOOP GEAR LUBRICATION SYSTEM

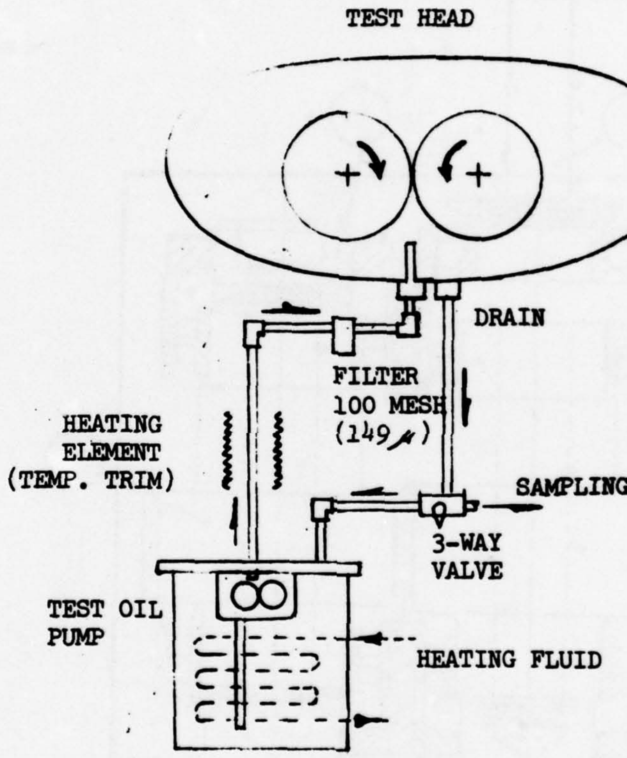
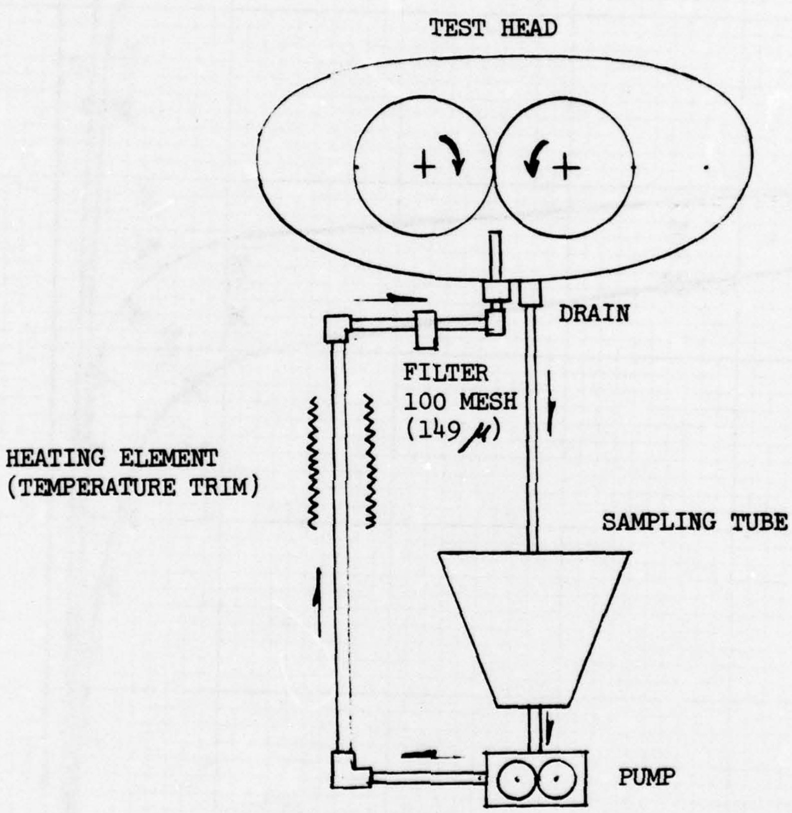


FIGURE 3. SCHEMATIC DIAGRAM CF SKF "CLEAN" CLOSED-LOOP GEAR LUBRICATION SYSTEM



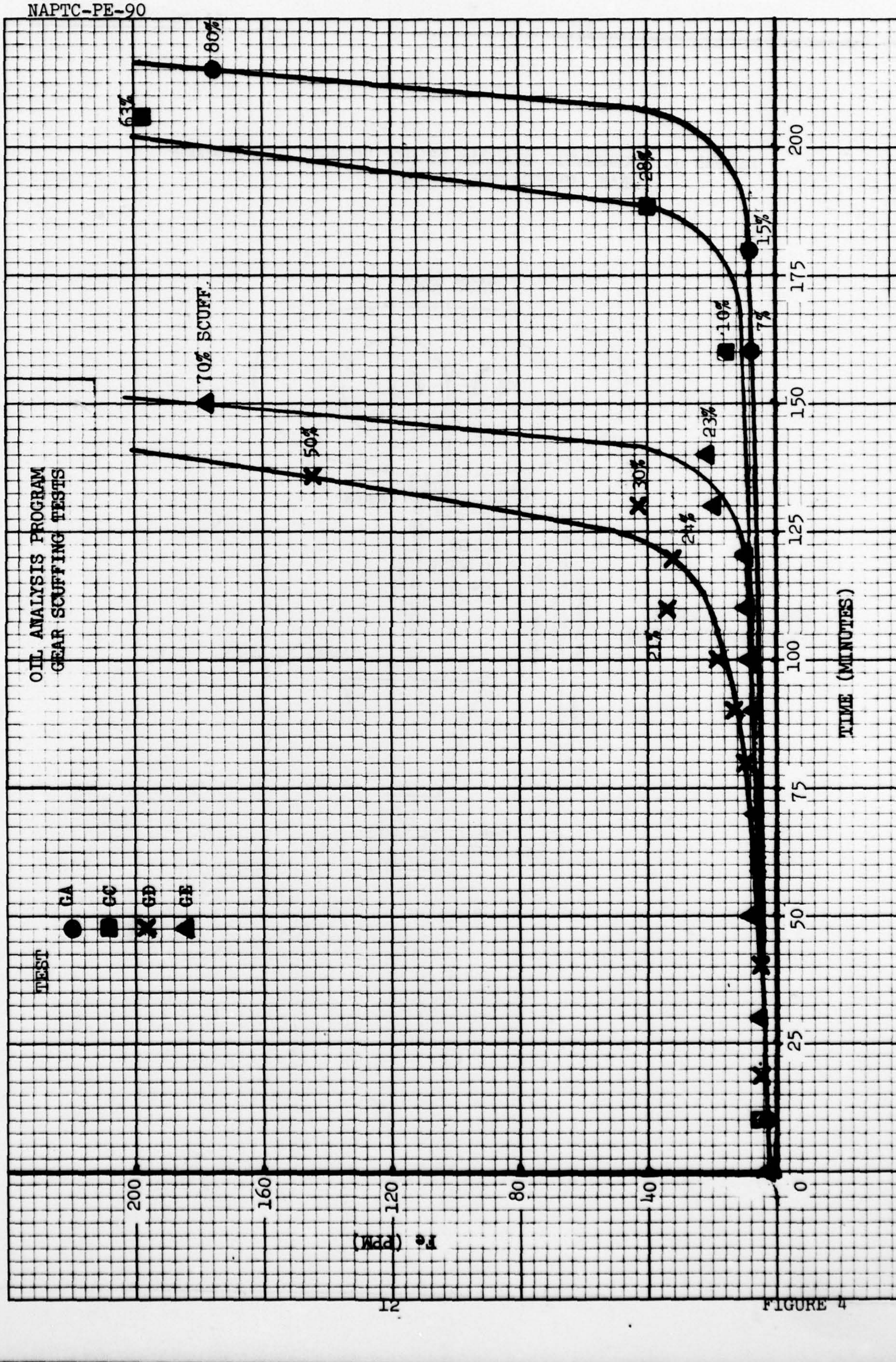

OIL ANALYSIS PROGRAM
GEAR SCUFFING TESTS
TEST
GA
GC
GD
GE
Fe (PPM)
TIME (MINUTES)
0
40
80
120
160
200
25
50
75
100
125
150
175
200
80%
63%
28%
15%
10%
7%
70% SCUFF.
50%
30%
23%
24%
21%

FIGURE 4

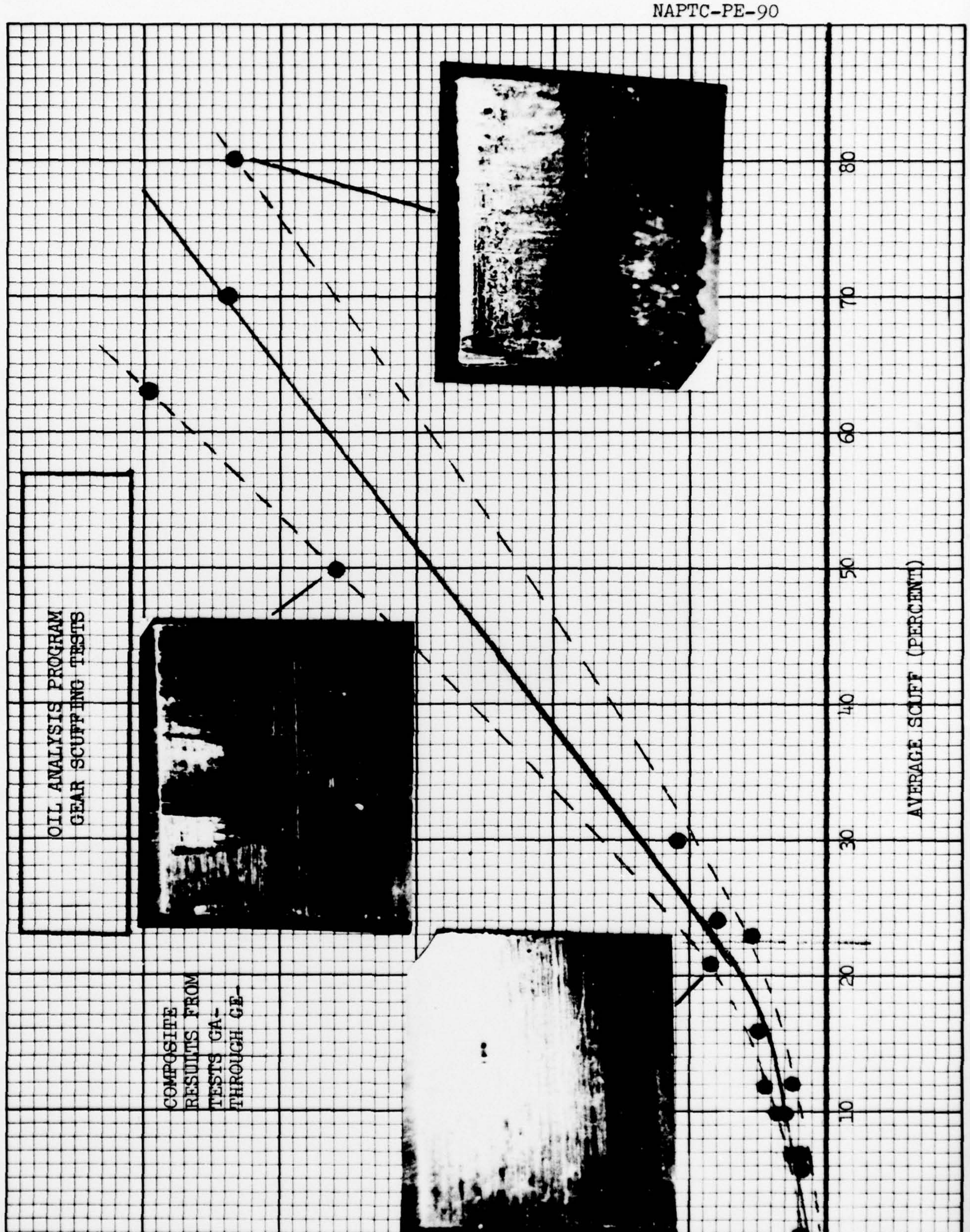

OIL ANALYSIS PROGRAM
GEAR SCUFFING TESTS
COMPOSITE
RESULTS FROM
TESTS GA-
THROUGH GE-
Fe (PPM)
0
40
80
120
160
200
AVERAGE SCUFF (PERCENT)
0
10
20
30
40
50
60
70
80

FIGURE 5

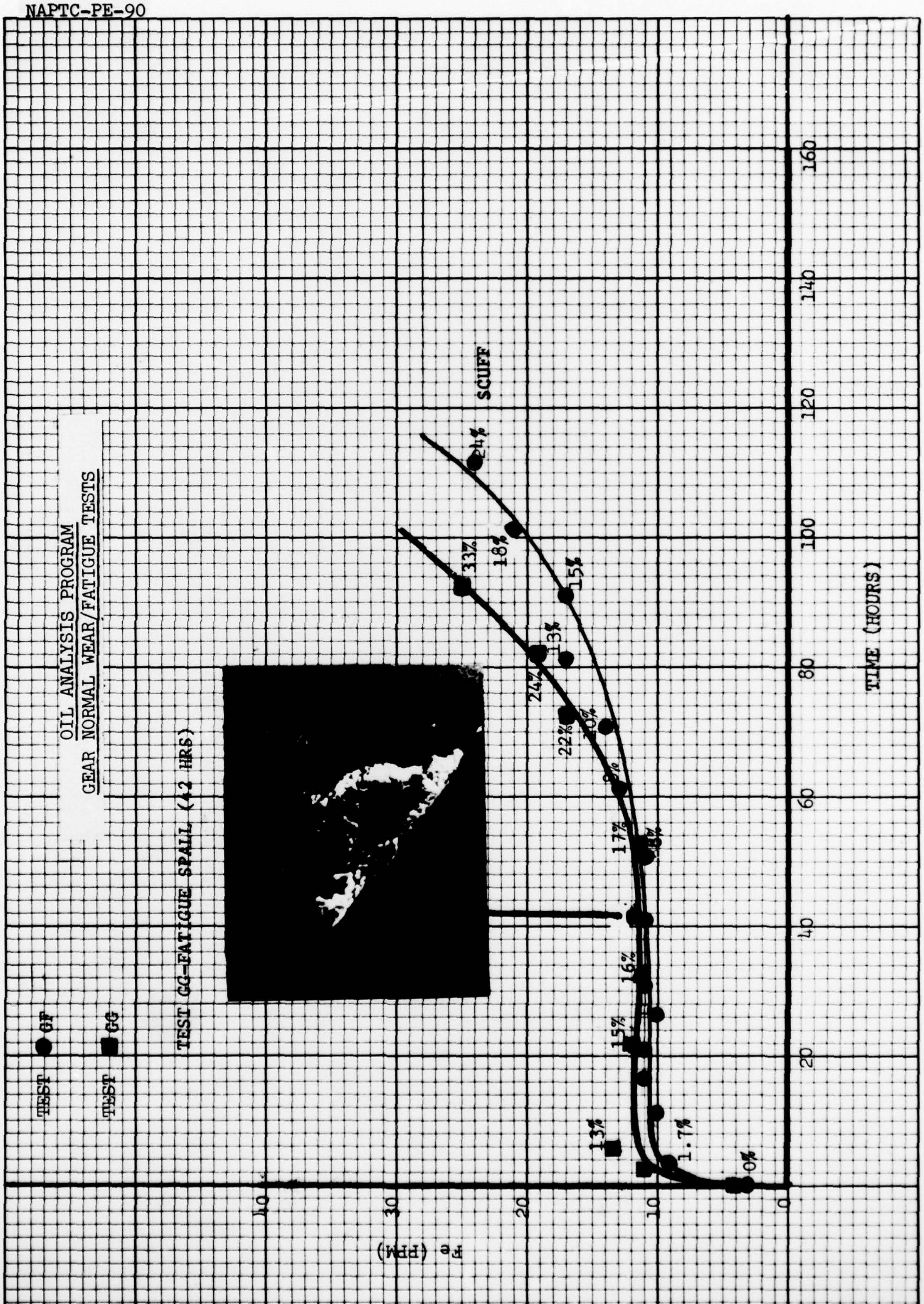

OIL ANALYSIS PROGRAM
GEAR NORMAL WEAR/FATIGUE TESTS
TEST ● GF
TEST ■ GG
TEST GG-FATIGUE SPALL (42 HRS)
SCUFF
TIME (HOURS)
Fe (PPM)
0
10
20
30
40
20
40
60
80
100
120
140
160
33%
18%
15%
24%
13%
24%
22%
17%
16%
15%
13%
1.7%
0%

FIGURE 6

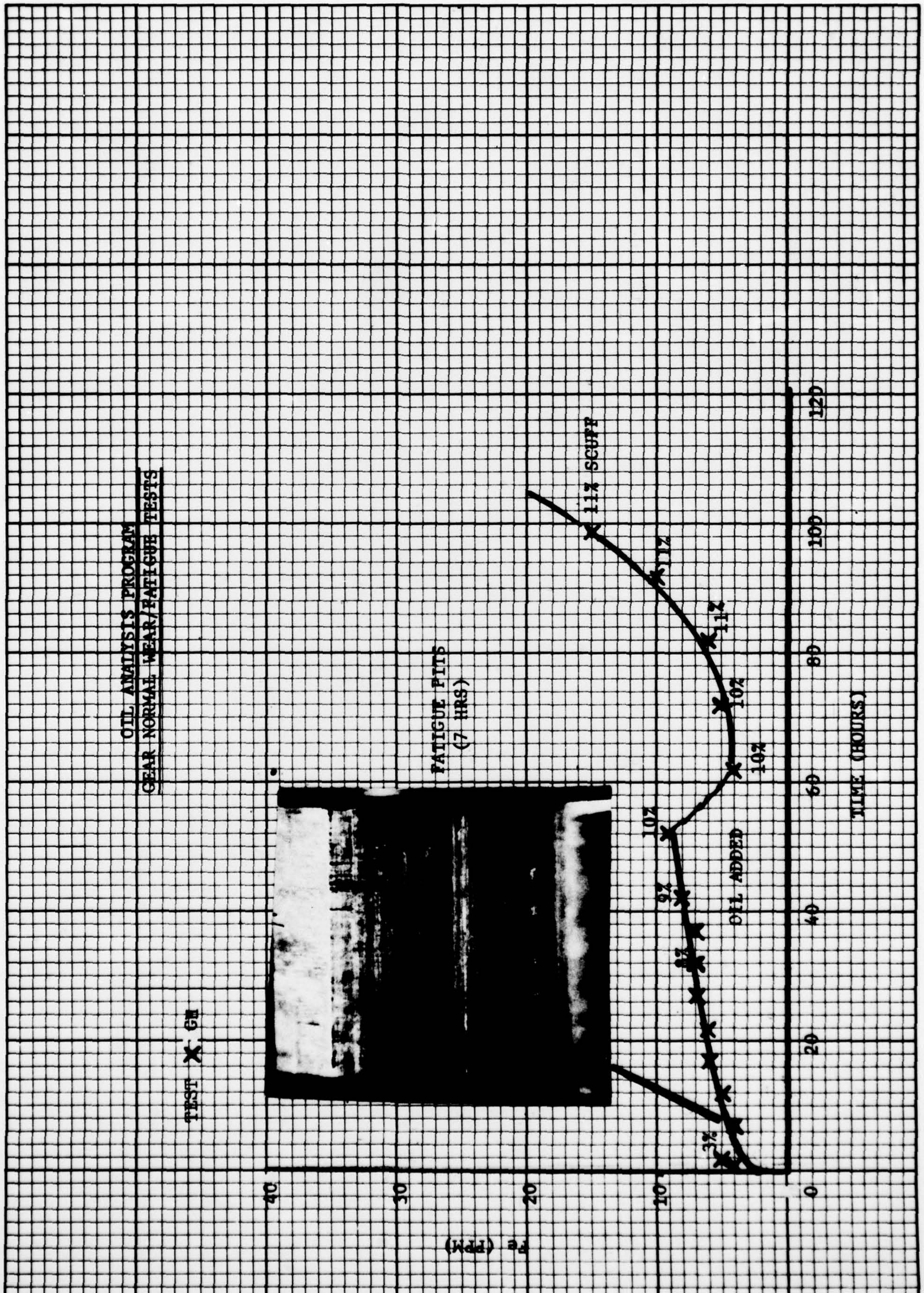

OIL ANALYSIS PROGRAM
GEAR NORMAL WEAR/FATIGUE TESTS
TEST X GM
FATIGUE PITS
(7 HRS)
11% SCUFF
OIL ADDED
TIME (HOURS)
Fe (PPM)

FIGURE 7

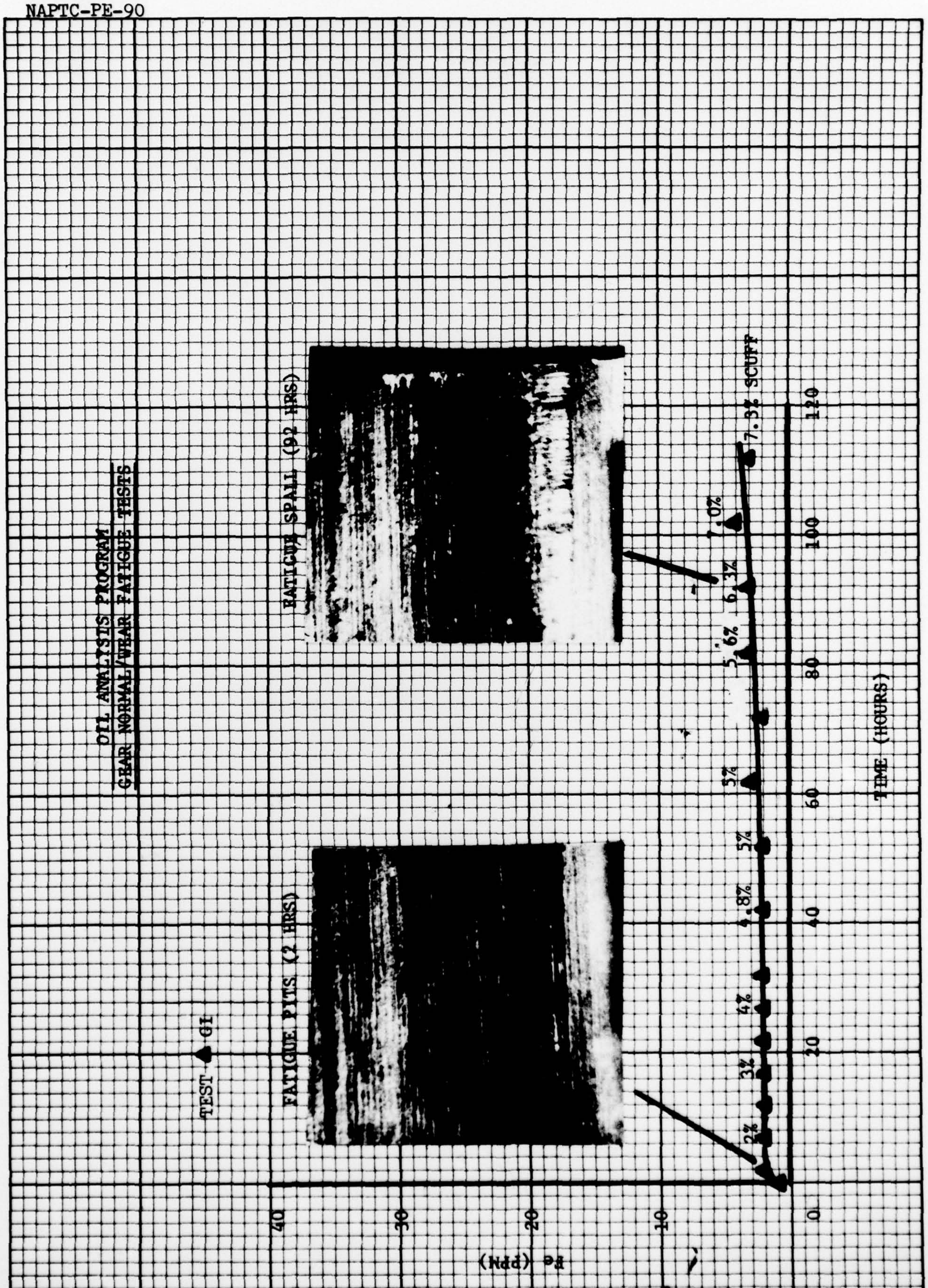

OIL ANALYSIS PROGRAM
GEAR NORMAL/WEAR FATIGUE TESTS
TEST ▲ G1
FATIGUE PITS (2 HRS)
FATIGUE SPALL (92 HRS)
2%
3%
4%
4.8%
5%
5%
5.6%
6.3%
7.0%
7.3% SCUFF
0
20
40
60
80
100
120
TIME (HOURS)
10
20
30
40
Fe (PPM)

FIGURE 8

TABLE I

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($X10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
SCUFFING	GA-								
TEST GEAR SET NARROW M-1425 WIDE L-1637 "A" SIDE		GA-0505-1	0	0	0	(0)	0	2	Circulated new oil
		GA-0505-2	0.17	0.1	40.3	(230)	0	3	Initial 10 min. run
		GA-0505-3	2.67	1.6	402.8	(2300)	7	7	Load increased in 40,300 N/m (230 PPI) increments (10 min. each) to 5% scuff. Then, run 1 hour at 402,800 N/m (2300 PPI).
		GA-0525-4	3.58	2.15	483.4	(2760)	80	175	Increased load to 483,400 N/m (2760 PPI) and obtained 15% scuff. Then, ran at constant load (35 min.). Scuff increased to 80%.
SCUFFING	GC-								
TEST GEAR SET NARROW M-1484 WIDE L-1597 "B" SIDE		GC-0625-1	0	0	0	(0)	0	2	Circulated new oil
		GC-0625-2	0.17	0.1	40.3	(230)	0	5	Initial 10 min. run
		GC-0635-3	2.67	1.6	402.8	(2300)	9.8	15	Load increased in 40,300 N/m (230 PPI) increments (10 min. each) to 5% scuff. Then, run 1 hour at 402,800 N/m (2300 PPI).
		GC-0655-4	3.43	2.06	523.6	(2990)	63	197	Increased load to 523,600 N/m (2990 PPI) and obtained 28% scuff. Then, ran at constant load (16 min.). Scuff increased to 63%.

TABLE I (CONTINUED)

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($X10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
SCUFFING	GD-								
TEST GEAR SET NARROW M-1396 WIDE L-1745 "A" SIDE		GD-0665-1	0	0	0	(0)	0	3	Circulated new oil
		GD-0665-2	0.17	0.1	40.3	(230)	0	4	Initial 10 min. run
		GD-0665-3	0.33	0.2	80.6	(460)	0	6	Increased load in 40,300 N/m (230 PPI) increments,run for 10 min. at each load.
		GD-0665-4	0.50	0.3	120.8	(690)	0	9	
		GD-0665-5	0.67	0.4	161.1	(920)	0	7	
		GD-0665-6	0.83	0.5	201.4	(1150)	1	7	
		GD-0665-7	1.0	0.6	241.7	(1380)	2.5	7	
		GD-0665-8	1.17	0.7	282.0	(1610)	5.7	8	
		GD-0665-9	1.33	0.8	322.2	(1840)	7.3	10	
		GD-0665-10	1.50	0.9	362.5	(2070)	10.4	13	
		GD-0665-11	1.67	1.0	402.8	(2300)	12.4	18	
		GD-0665-12	1.83	1.1	443.1	(2530)	20.8	34	
		GD-0665-13	2.0	1.2	483.4	(2760)	23.8	32	
		GD-0665-14	2.17	1.3	523.6	(2990)	28.9	43	
		GD-0665-15	2.33	1.4	563.9	(3220)	50.0	144	

TABLE I (CONTINUED)

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($X10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
SCUFFING									
	GE-								
TEST GEAR SET NARROW M-1396 WIDE L-1745 "B" SIDE		GE-0715-1	0	0	0	(0)	0	2	Circulated new oil
		GE-0715-2	0.17	0.1	40.3	(230)	0	4	Initial load run
		GE-0715-3	0.33	0.2	80.6	(460)	0	5	Increased load in 40,300 N/m (230 PPI) increments, run for 10 min. at each load.
		GE-0715-4	0.50	0.3	120.8	(690)	0	5	
		GE-0715-5	0.67	0.4	161.1	(920)	0	5	
		GE-0715-6	0.83	0.5	201.4	(1150)	0	8	
		GE-0715-7	1.0	0.6	241.7	(1380)	0	6	
		GE-0715-8	1.17	0.7	282.0	(1610)	1.0	6	
		GE-0715-9	1.33	0.8	322.2	(1840)	1.8	7	
		GE-0715-10	1.50	0.9	362.5	(2070)	2.0	6	
		GE-0715-11	1.67	1.0	402.8	(2300)	3.4	8	
		GE-0715-12	1.83	1.1	443.1	(2530)	6.1	9	
		GE-0715-13	2.00	1.2	483.4	(2760)	12.2	9	
		GE-0715-14	2.17	1.3	523.6	(2990)	16.2	19	
		GE-0715-15	2.33	1.4	563.9	(3220)	23.0	21	
		GE-0715-16	2.50	1.5	604.2	(3450)	69.6	177	

TABLE I (CONTINUED)

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($X10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE PITS	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
FATIGUE	GF-									
TEST GEAR SET NARROW M-1485 WIDE L-1659 "A" SIDE		GF-0765-1	0	0	0	(0)	NONE	0	3	Circulated new oil
		GF-0765-2	0.83	0.5	201.4	(1150)		0	8	Load increased from 40,300 to 201,400 N/m (230 to 1150 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GF-0775-3	1.50	0.9	362.5	(2070)		1.7	8	Load increased from 201,400 to 362,500 N/m (1150 to 2070 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GF-0775-4	2.5	1.5	362.5	(2070)		3.5	9	Constant load for 1 hour
		GF-0775-5	3.5	2.1	362.5	(2070)		4.1	9	
		GF-0785-6	4.5	2.7	362.5	(2070)		4.3	10	
		GF-0785-7	5.5	3.3	362.5	(2070)		4.6	9	
		GF-0785-8	6.5	3.9	362.5	(2070)		4.6	9	
		GF-0795-9	11.5	6.9	362.5	(2070)		5.5	10	Constant load for 5 hours
		GF-0805-10	16.5	9.9	362.5	(2070)		6.3	11	
		GF-0835-11	21.5	12.9	362.5	(2070)		6.7	11	
		GF-0845-12	26.5	15.9	362.5	(2070)		7.0	10	
		GF-0855-13	31.5	18.9	362.5	(2070)		7.2	11	
		GF-0865-14	41.5	24.9	362.5	(2070)		8.1	11	Constant load for 10 hours
		GF-0875-15	51.5	30.9	362.5	(2070)		8.2	11	
		GF-0905-16	61.5	36.9	362.5	(2070)		8.2	13	
		GF-0915-17	71.5	42.9	362.5	(2C70)		10	14	
		GF-0925-18	81.5	48.9	362.5	(2070)		13	17	
		GF-0935-19	91.5	54.9	362.5	(2070)		15	17	
		GF-0945-20	101.5	60.9	402.8	(2300)		18	21	Increased load to 402,800 N/m (2300 PPI) constant load for 10 hours.
		GF-0975-21	111.5	66.9	402.8	(2300)		24.2	24	Constant load for 10 hours

ABORT TEST: NO PITTING FAILURES

TABLE I (CONTINUED)

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($X10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE PITS	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
FATIGUE										
	GG-									
TEST GEAR SET NARROW M-1485 WIDE L-1659 "B" SIDE		GG-0995-1	0	0	0	(0)	-	0	4	Circulated new oil
		GG-0995-2	0.83	0.5	201.4	(1150)	NONE	0	4	Load increased from 40,300 to 201,400 N/m (230 to 1150 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GG-1005-3	1.83	1.1	443.1	(2530)		9	11	Load increased from 201,400 to 443,100 N/m (1150 to 2530 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GG-1005-4	2.83	1.7	443.1	(2530)		9.8	11	Constant load for 1 hour
		GG-1045-5	3.83	2.3	443.1	(2530)		11.4	13	
		GG-1045-6	4.83	2.9	443.1	(2530)		11.9	13	
		GG-1055-7	5.83	3.5	443.1	(2530)		12.5	14	
		GG-1055-8	6.83	4.1	443.1	(2530)		13	13	
		GG-1065-9	11.83	7.1	443.1	(2530)		13.5	10	Constant load for 5 hours
		GG-1065-10	16.83	10.1	443.1	(2530)		13.8	9	
		GG-1075-11	21.83	13.1	443.1	(2530)		14.7	12	
		GG-1075-12	26.83	16.1	443.1	(2530)		15.2	11	
		GG-1085-13	31.83	19.1	443.1	(2530)		15.6	11	
		GG-1115-14	41.83	25.1	443.1	(2530)	SPALL 2 TEETH	16.7	12	Constant load for 10 hours
		GG-1125-15	51.83	31.1	443.1	(2530)	SAME	17.4	11	
		GG-1135-16	61.83	37.1	443.1	(2530)	3 TEETH	18	10	
		GG-1145-17	71.83	43.1	443.1	(2530)	4 TEETH	22	17	
		GG-1155-18	81.83	49.1	443.1	(2530)	SAME	24.5	19	
		GG-1185-19	91.83	55.1	443.1	(2530)	SAME	33.4	25	

ABORT TEST: SPALLS ON 4 TEETH

TABLE I (CONTINUED)

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. ($X10^6$)	TOOTH LOAD N/m X 10^3	TOOTH LOAD (PPI)	FAILURE PITS	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
FATIGUE	GH-									
TEST GEAR SET NARROW M-1997 WIDE M-1750 "A" SIDE		GH-2255-1	0	0	0	(0)	-	0	1	New oil
		GH-2255-2	0	0	0	(0)	-	0	1	Circulated new oil
		GH-2255-3	0.83	0.5	201.4	(1150)	NONE	0	4	Load increased from 40,300 to 201,400 N/m (230 to 1150 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GH-2255-4	1.83	1.1	443.1	(2530)	NONE	2.8	5	Load increased from 201,400 to 443,100 N/m (1150 to 2530 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GH-2265-5	6.83	4.1	443.1	(2530)	MILD-12 TEETH	4	4	Constant load for 5 hours
		GH-2275-6	11.83	7.1	443.1	(2530)	NO CHANGE	5.4	5	
		GH-2305-7	16.83	10.1	443.1	(2530)		6.5	6	
		GH-2305-8	21.83	13.1	443.1	(2530)		6.7	6	
		GH-2315-9	26.83	16.1	443.1	(2530)		7.6	7	
		GH-2315-10	31.83	19.1	443.1	(2530)		8.1	7	
		GH-2325-11	36.83	22.1	443.1	(2530)		8.4	7	
		GH-2325-12	41.83	25.1	443.1	(2530)		9.0	8	
		GH-2335-13	51.83	31.1	443.1	(2530)		10.0	9	Constant load for 10 hours (oil added)
		GH-2345-14	61.83	37.1	443.1	(2530)		10.3	4	
		GH-2385-15	71.83	43.1	443.1	(2530)		10.8	5	
		GH-2395-16	81.83	49.1	443.1	(2530)		11	6	
		GH-2405-17	91.83	55.1	443.1	(2530)		11.3	10	
		GH-2415-18	98.83	59.3	483.4	(2760)		11.4	15	Load increased to 483,400 N/m (2760 PPI) constant load for 7 hours

ABORT TEST: NO SIGNIFICANT INCREASE IN FATIGUE PITTING

TABLE I (CONTINUED)

OIL ANALYSIS PROGRAM SUMMARY OF GEAR BENCH TESTS

TYPE TEST	TEST IDENT.	SAMPLE NO.	TOTAL TIME (HRS)	TOTAL REV. $(X10^6)$	TOOTH LOAD $N/m \times 10^3$	TOOTH LOAD (PPI)	FAILURE PITS	FAILURE AVG. SCUFF (PERCENT)	NOAP Fe (PPM)	REMARKS
FATIGUE										
	GI-									
TEST GEAR SET NARROW M-1997 WIDE M-1750 "B" SIDE		GI-2455-1	0	0	0	(0)	-	0	1	New oil
		GI-2455-2	0	0	0	(0)	-	0	1	Circulated new oil
		GI-2455-3	1.0	0.6	241.8	(1380)	-	0	1	Load increased from 40,300 to 241,800 N/m (230 to 1380 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GI-2465-4	2.0	1.2	483.4	(2760)	MILD 2 TEETH	1.6	2	Load increased from 241,800 to 483,400 N/m (1380 to 2760 PPI) in 40,300 N/m (230 PPI) increments (10 min. each).
		GI-2475-5	7.0	4.2	483.4	(2760)	MILD 3 TEETH	2	2	Constant load for 5 hours
		GI-2475-6	12.0	7.2	483.4	(2760)	NO CHANGE	2.6	2	
		GI-2485-7	17.0	10.2	483.4	(2760)		3	2	
		GI-2485-8	22.0	13.2	483.4	(2760)		3.7	2	
		GI-2515-9	27.0	16.2	483.4	(2760)		4	2	
		GI-2515-10	32.0	19.2	483.4	(2760)		4.4	2	
		GI-2525-11	42.0	25.2	483.4	(2760)		4.8	2	Constant load for 10 hours
		GI-2535-12	52.0	31.2	483.4	(2760)		5	2	
		GI-2545-13	62.0	37.2	483.4	(2760)		5	3	
		GI-2555-14	72.0	43.2	483.4	(2760)		5.3	2	
		GI-2585-15	82.0	49.2	523.6	(2990)		5.6	3	Load increased to 523,600 N/m (2990 PPI) constant load for 10 hours.
		GI-2595-16	92.0	55.2	523.6	(2990)	4TH TOOTH LARGE SPALL	6.3	3	
		GI-2605-17	102.0	61.2	563.9	(3220)		7	4	Load increased to 563,900 N/m (3220 PPI) constant load for 10 hours
		GI-2615-18	112.0	67.2	563.9	(3220)		7.3	3	

ABORT TEST: NO SIGNIFICANT INCREASE IN FATIGUE PITTING

REFERENCES

1. AUTHORIZATION - Naval Air Engineering Center Project Order No. NAEC-PO5-8020 of 15 October 1974.